Measuring the ion current in electrical discharges using radio-frequency current and voltage measurements

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This letter describes a technique for measuring the ion current at a semiconductor wafer that is undergoing plasma processing. The technique relies on external measurements of the radio-frequency (rf) current and voltage at the wafer electrode. The rf signals are generated by the rf bias power which is normally applied to wafers during processing. There is no need for any probe inserted into the plasma or for any additional power supplies which might perturb the plasma. To test the technique, comparisons were made with dc measurements of ion current at a bare aluminum electrode, for argon discharges at 1.33 Pa, ion current densities of 1.3–13 mA/cm^2, rf bias frequencies of 0.1–10 MHz, and rf bias voltages from 1 to 200 V. Additional tests showed that ion current measurements could be obtained by the rf technique even when electrically insulating wafers were placed on the electrode and when an insulating layer was deposited on the electrode.
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Plasmas are widely used by industry to process materials. Substrate wafers exposed to plasmas are bombarded by reactive chemical species and energetic positive ions, resulting in the deposition or etching of films. To obtain the best possible results from plasma processing, the fluxes, energies, and velocities of the incident ions and neutrals must be carefully controlled. Unfortunately, plasma reactors are subject to many types of drift, so that settings of the control parameters that initially produced optimal results may no longer produce acceptable results at later times. This problem could be solved if sensors were available to measure the relevant properties of the incident ions and neutrals. Such sensors could be used to detect process drift, diagnose its origin, and take corrective action, if needed.

One important parameter is the total ion current at the wafer. Since negative ions are repelled from the wafer, the total ion current is the sum of the fluxes of each positive ionic species, each weighted by its charge. Typically, most ionic species in etching and deposition plasmas are singly charged, so the total ion current is closely related to the total ion flux. Etch rates, etch profiles, deposition rates and damage rates all depend on the total ion current or flux.

Many methods have been used to measure ion current, but they are not suitable for monitoring commercial processes in industrial reactors. For example, Langmuir probes are often used in research, but they measure the ion current *within* the plasma, not at the wafer. Furthermore, materials sputtered from Langmuir probes may contaminate wafers. Probe measurements may be upset by the large rf currents circulating in plasma reactors. Conversely, the voltages applied to the probe may perturb the plasma. Finally, in many industrial applications, insulating layers are formed on the probes, causing them to fail.

The ion current may also be measured by sampling the ions through an orifice, as in mass spectrometry. Mass spectrometers, however, are difficult to calibrate and are not compatible with many industrial processes. Although a calibrated ion-sampling orifice can be incorporated into an electrode to measure the ion current there,[1] wafers placed on the electrode will cover the orifice, interrupting the flow of ions and preventing the ion current measurement. To avoid this problem, devices for measuring ion current have been fabricated on specially designed test wafers. But the difficulty of transferring the signal from the wafer makes such devices too impractical for use with actual wafers being processed. Furthermore, all of these techniques, including mass spectrometry[2] suffer from problems caused by the deposition of insulating layers.

Ion currents at an electrode have been measured by a noninvasive technique[3,4] in which a large, negative dc voltage is imposed on the electrode itself, and the resulting dc current at the electrode is measured. If an insulating layer or insulating wafer is on the electrode, however, no dc current will be measured, and this technique will fail. Also, this ''dc-biased electrode'' technique strongly perturbs the plasma sheath adjacent to the electrode. This may alter the ion energies at the electrode, and even the ion current itself.[3]

This letter presents a new method for measuring the ion current at a wafer during processing. It does not require any hardware be installed inside the reactor; thus it cannot contaminate wafers. Instead, it relies on rf current and voltage measurements made externally. Although several methods have previously been proposed for estimating the ion current at an electrode from rf measurements,[3,5–7] those methods require assumptions about the power dissipation mechanisms within the discharge and the symmetry of the discharge. The uncertainty of the assumptions makes those methods inaccurate and impractical. In contrast, the method presented here does not require such assumptions. Furthermore, it, unlike previous methods, has been designed for high-density plasmas, which are increasingly used for the most challenging etching and deposition processes.

High-density plasma reactors usually contain two power

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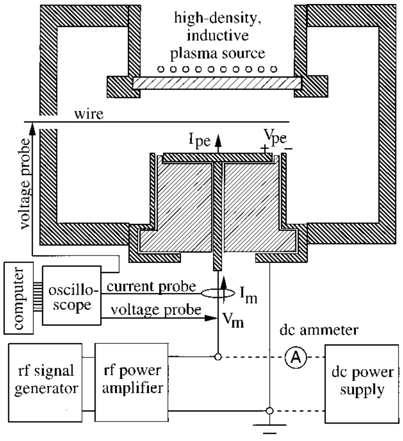

FIG. 1. A diagram of the measurement system and the high-density plasma reactor (see Refs. 8 and 9) in which it was installed. Measurements made by the probes connected to the lower electrode are used to determine the waveforms of current and voltage on that electrode, $I_{pe}(t)$ and $V_{pe}(t)$, as well as the ion current at that electrode. During the experiment, a wire probe (see Ref. 12) was installed to measure sheath voltages, but it is not necessary for ion current measurements. A dc power supply and a dc ammeter used for independent, dc measurements of ion current are also shown.

sources: one to generate the plasma and a second, the ''rf bias'' power supply, which is applied to wafers to control ion bombardment energies. Here, we make use of the latter. The current and voltage signals generated by the rf bias power supply, under normal operating conditions, contain the desired information. There is no need for additional power supplies to apply additional currents or voltages that could perturb the plasma.

Figure 1 shows a diagram of the measurement system and the reactor[8,9] in which it is installed. The inductive, high-density plasma source on top of the reactor is always powered at 13.56 MHz. Variable frequency rf bias power is supplied to the lower electrode by a sinusoidal signal generator and a power amplifier. On the lead that powers the lower electrode, current and voltage probes are mounted. Signals acquired by the probes are digitized by an oscilloscope and transferred to a computer for Fourier analysis. Procedures described previously[10] account for phase errors in the probes and for the stray impedance between the probes and the electrode, allowing one to determine $I_{pe}(t)$ and $V_{pe}(t)$, the current and voltage waveforms at the electrode itself. Examples of the waveforms are shown in Fig. 2.

The electrode voltage, $V_{pe}(t)$, is the sum of $V_{ps}(t)$, the voltage drop across the sheath at the rf-powered electrode, and $V_{gs}(t)$, the voltage drop across the sheath at opposing, grounded surfaces. Using a wire probe inserted into the plasma (as shown in Fig. 1) and techniques described previously,[11,12] the rf components of the $V_{ps}(t)$ and $V_{gs}(t)$ waveforms were determined. Examination of the resulting waveforms, shown in Fig. 2(a), reveals that the peak-to-peak sheath voltages are not equal, as assumed in Ref. 3, nor is one many times greater than the other, as assumed in Ref. 6. Therefore, methods of determining ion currents based on those assumptions will be in error.

The $I_{pe}(t)$ waveform is the sum of several currents, which can be expressed as

$$I_{pe}(t)=-I_0+I_e \exp[V_{ps}(t)/T_e]+C_s(t)dV_{ps}/dt. \tag{1}$$

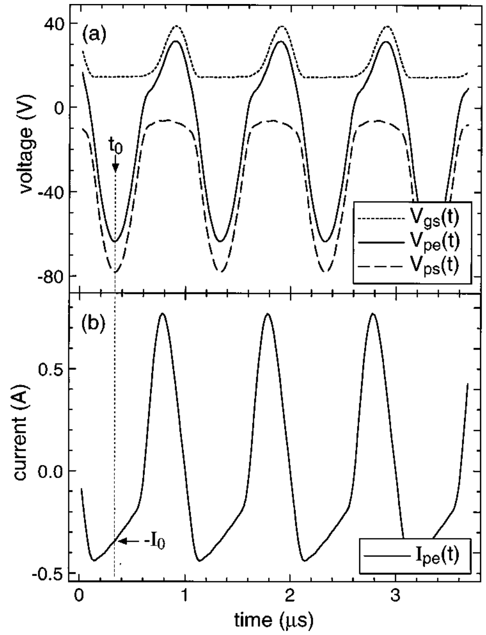

FIG. 2. Waveforms of (a) the voltage on the powered electrode, $V_{pe}(t)$, the voltage across the sheath at the powered electrode, $V_{ps}(t)$, the voltage across the ground sheath, $V_{gs}(t)$, and (b) the current at the powered electrode, $I_{pe}(t)$. At time t_0, when $V_{pe}(t)$ and $V_{ps}(t)$ are minimized, $I_{pe}(t)$ is equal to the ion current, $-I_0$. Data were obtained for an argon discharge at 1.3 Pa, a bias frequency of 1 MHz, and an ion current (determined independently from dc measurements) of 0.32 A.

The first term is the ion current. It is negative, corresponding to a flow of positive ions from the plasma to the electrode. The second term is the electron current, for a Maxwell–Boltzmann distribution of plasma electrons at temperature T_e (in volts). The final term is the sheath displacement current. The displacement current arises because the sheath contains a net positive charge, $Q(t)$, which is compensated by electrons on the electrode surface. As the sheath charge varies during an rf cycle, the surface charge must also vary, causing a current dQ/dt to flow in the electrode's electrical connections. In Eq. (1), this current has been expressed using the instantaneous sheath capacitance, $C_s(t)=dQ/dV_{ps}$.

When the voltage $V_{ps}(t)$ is strongly negative, electrons in the plasma are strongly repelled from the electrode, and the electron current in Eq. (1) will be negligibly small. Furthermore, when $dV_{ps}/dt=0$, the charging current is zero. Therefore, at t_0, the time when $V_{ps}(t)$ reaches its minimum value, both the electron current and the charging current are negligible. The value of the current waveform at that time is therefore equal to the ion current,

$$I_{pe}(t_0)=-I_0, \tag{2}$$

as indicated in Fig. 2. Thus, the ion current can be determined using very general arguments, with no need for a detailed model of the displacement current or the electron current. Furthermore, in Fig. 2(a) (and throughout the experimental range given below) the minimum in the electrode voltage, $V_{pe}(t)$, occurs at the same time as the minimum in $V_{ps}(t)$. Thus t_0 (and I_0) can be determined from $V_{pe}(t)$ and $I_{pe}(t)$ alone. Wire probe measurements of the individual sheath voltages are not necessary.

Values of $I_{pe}(t_0)$ were obtained for argon discharges at 1.33 Pa, rf bias voltages from 1 to 200 V, rf bias frequencies

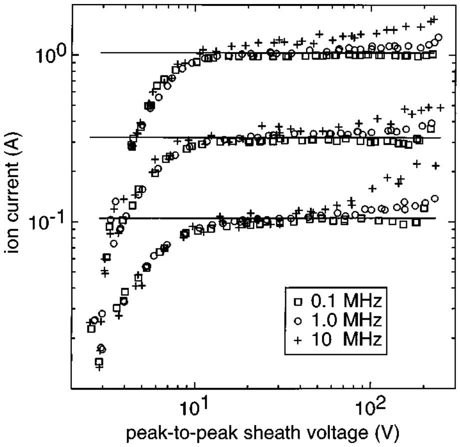

FIG. 3. Comparison of rf measurements of ion current based on Eq. (2) (symbols) and dc measurements of ion current (lines). Measurements were performed at varying rf bias voltages [given on the x axis as peak-to-peak amplitudes of the sheath voltage $V_{ps}(t)$], and varying rf bias frequencies of 0.1–10 MHz. Power was supplied to the inductive plasma source at a fixed frequency of 13.56 MHz, at (from bottom to top) 60, 120, and 350 W, corresponding to dc ion currents of 0.105, 0.32, and 1.05 A, and dc ion current densities of 1.3, 4.0, and 13 mA/cm^2.

of 0.1, 1, and 10 MHz, and inductive source powers of 60, 120, and 350 W. At each source power, the rf bias power supply was temporarily disconnected and a dc power supply was connected to perform independent measurements of the ion current, using the dc-biased electrode method mentioned above.[3,4] Results from both methods are shown in Fig. 3. Good agreement was obtained over most of the experimental range, but not at high rf bias frequencies or at peak-to-peak sheath voltages <10 V. At these low voltages, electrons are not repelled strongly enough by the electrode, and some electrons are collected even at t_0. The collected electrons cancel part of the ion current, forcing $I_{pe}(t_0)$ to zero as the voltage approaches zero. Nevertheless, such low voltages are not used by industry. To accelerate ions to desired energies, tens of hundreds of electron volts, the rf bias in industrial reactors must supply tens or hundreds of volts of peak-to-peak sheath voltage.

The deviation at high frequencies is more difficult to explain. It could in part result from the limited bandwidth of the current and voltage probes. Their accuracy starts to degrade around 25–30 MHz, but to faithfully reproduce the waveforms requires measurement of signals at and above 60 MHz, the sixth harmonic of the 10 MHz fundamental frequency. Alternatively, because the dc and rf measurements are not performed simultaneously, it is possible that the increase in ion current measured by the rf technique is a real effect, indicating that the high-frequency rf bias produces an increase in plasma density and in ion current. Finally, the discrepancy might be explained by a time modulation of the ion current. Simulations[13] predict that the ion current should vary with time when the rf bias frequency is comparable to the ion transit frequency. Under these circumstances, $I_{pe}(t_0)$ would still be equal to the ion current at time t_0, but it would not necessarily agree with the time-averaged value of the ion current provided by the dc measurement.

Additional tests were performed with electrodes partially covered by silicon wafers. Over the area covered by a wafer, no dc current is collected from the plasma, causing dc measurements of ion current to fail. In contrast, rf measurements of ion current were not affected.

Measurements were also performed in Ar/SF_6 plasmas at 2.66 Pa. Results similar to those shown in Figs. 2 and 3 were observed. Within minutes of beginning the Ar/SF_6 measurements, however, an insulating layer formed on the electrode, causing the dc-biased electrode method to fail, and preventing a detailed comparison as in Fig. 3. During the time that the insulating layer was forming, time-dependent changes in the ion current were detected by the rf measurement technique. Presumably, these changes result from a decreased density of gas phase reactant species while the insulating layer was being formed. The changes in the ion current during this ''conditioning'' of the electrode surface are an example of the sort of uncontrolled processes that the measurement technique proposed here could be used to monitor.

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